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Lead and s-process elements in stars of various metallicities: AGB predictions compared with observation

D. Delaude[1], R. Gallino[1], S. Cristallo[2], O. Straniero[2], L. Husti[3] and S. Ryan[4]

[1] Dipartimento di Fisica dell'Universitá di Torino, via P.Giuria 1, 10125 Torino, Italy
[2] Osservatorio Astronomico di Collurania, 64100 Teramo, Italy
[3] University of Bucharest, Romania
[4] Open University, Walton Hall, Milton Keynes, UK

Abstract. We present AGB predictions for all heavy elements within a large range of ^{13}C-pocket efficiencies for stars of different metallicities, and compare them in detail with a number of spectroscopic observations of *s*-rich and lead-rich in the Galaxy. The current concept of the *s*-process efficiency, specified by the [hs/ls] index, is shown to be inappropriate for the metal poor AGB stars and a second independent index, [Pb/hs] or [Pb/ls], needs to be introduced. The state-of-the-art concerning the interpretation of lead stars allows a very large spread of [Pb/hs] in metal poor stars, as typically observed. We discuss agreements and discrepancies for a large range of elements.

Key words. AGB stars – AGB nucleosynthesis – Lead stars – *s*-process

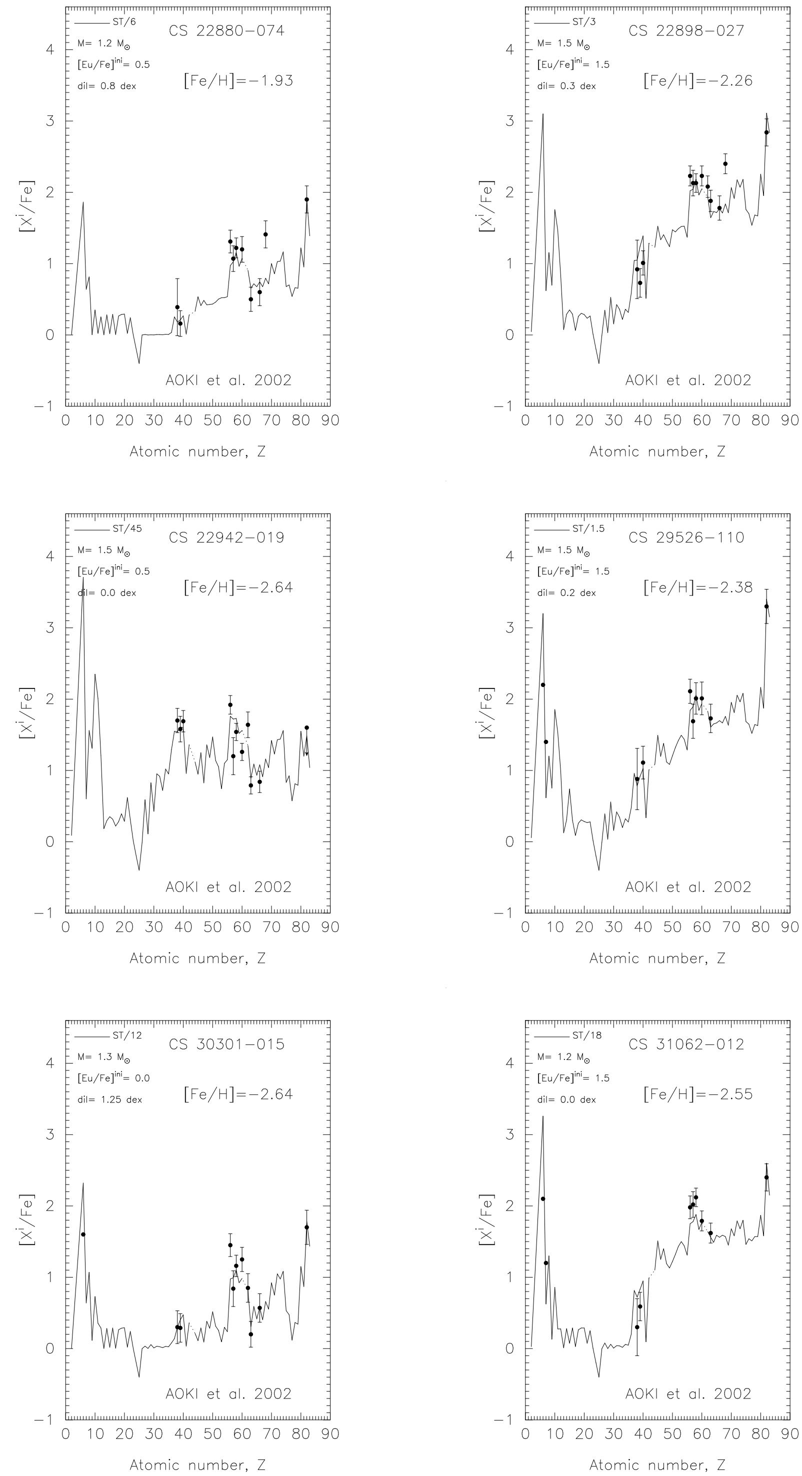
1. Introduction

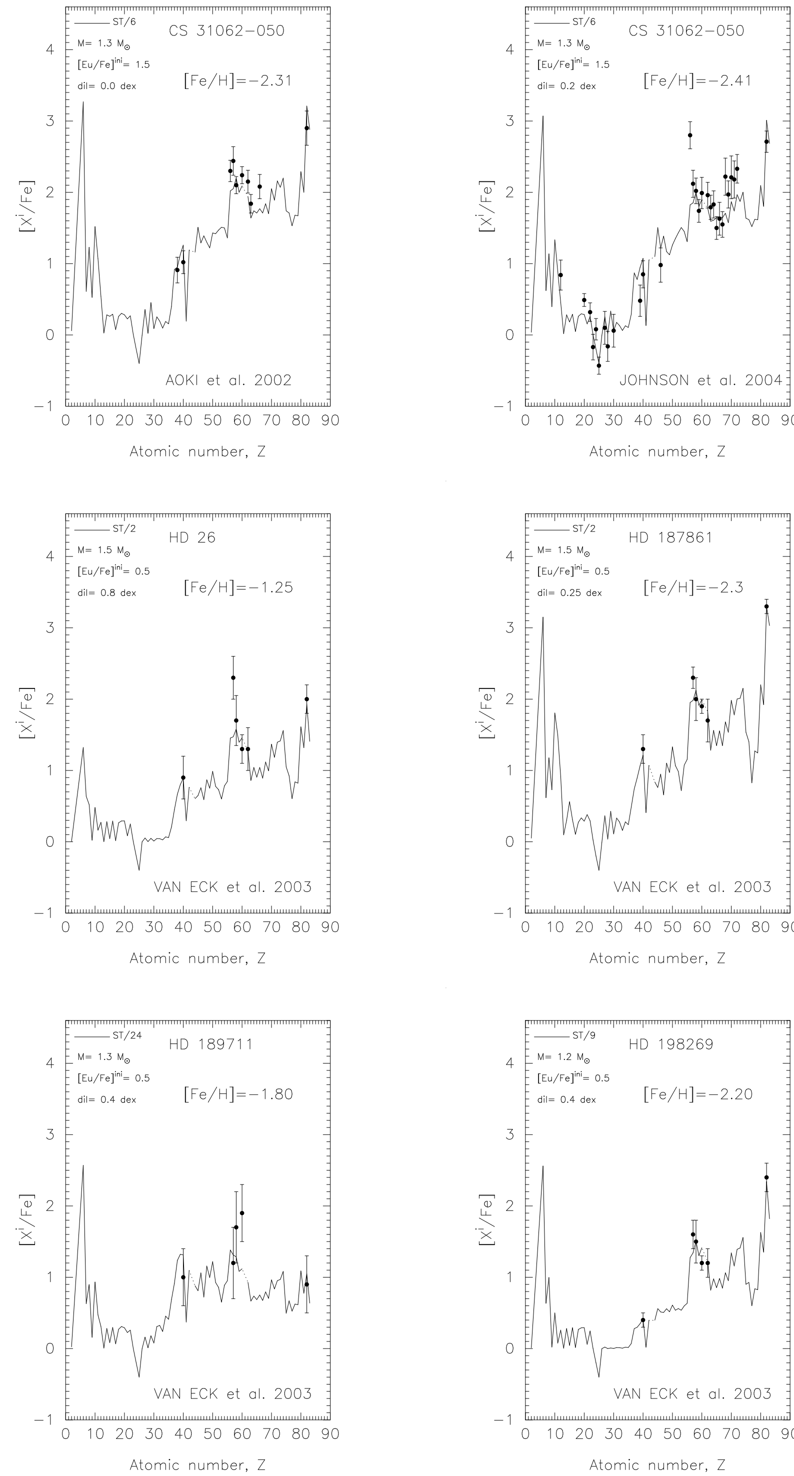
Spectroscopic detection of lead requires very high-resolution spectroscopy. This is why lead-rich stars have only been observed in the last few years. As discussed in Travaglio et al. (2001), the *s*-process can bring forth a large production of lead in AGB stars at low metallicity. In fact lead and bismuth are at the termination points of the *s*-fluence. Using a primary-like neutron source (like the $^{13}C(\alpha,n)^{16}O$ reaction in interpulse phases) and starting with a very low initial metallicity, most iron seeds are converted into ^{208}Pb. So, when third dredge up episodes mix the neutron capture products into the envelope, the star appears *s*-enhanced and lead-rich.

Send offprint requests to: R. Gallino
Correspondence to: gallino@ph.unito.it

2. The intrinsic index [Pb/hs]

Commonly s-rich stars are classified as either intrinsic or extrinsic, with extrinsic being those stars that become *s*-enhanced not because of internal nucleosynthesis but through receiving *s*-rich material from a companion in a binary system by mass transfer. To characterize neutron capture process efficiencies, without distinguishing between these two types of objects, usually the intrinsic index [hs/ls] is used (where hs is the average abundance of the heavy *s*-elements Ba, La, Nd, Sm, and ls of the light *s*-elements Y, Zr). However, at low metal-


ST/6
M= 1.2 $M_\odot$
$[Eu/Fe]^{ini}$= 0.5
dil= 0.8 dex
CS 22880-074
[Fe/H]=−1.93
AOKI et al. 2002
ST/3
M= 1.5 $M_\odot$
$[Eu/Fe]^{ini}$= 1.5
dil= 0.3 dex
CS 22898-027
[Fe/H]=−2.26
AOKI et al. 2002
ST/45
M= 1.5 $M_\odot$
$[Eu/Fe]^{ini}$= 0.5
dil= 0.0 dex
CS 22942-019
[Fe/H]=−2.64
AOKI et al. 2002
ST/1.5
M= 1.5 $M_\odot$
$[Eu/Fe]^{ini}$= 1.5
dil= 0.2 dex
CS 29526-110
[Fe/H]=−2.38
AOKI et al. 2002
ST/12
M= 1.3 $M_\odot$
$[Eu/Fe]^{ini}$= 0.0
dil= 1.25 dex
CS 30301-015
[Fe/H]=−2.64
AOKI et al. 2002
ST/18
M= 1.2 $M_\odot$
$[Eu/Fe]^{ini}$= 1.5
dil= 0.0 dex
CS 31062-012
[Fe/H]=−2.55
AOKI et al. 2002
$[X^i/Fe]$
Atomic number, Z



ST/6
CS 31062−050
M= 1.3 M$_\odot$
[Eu/Fe]^{ini}= 1.5
dil= 0.0 dex
[Fe/H]=−2.31
AOKI et al. 2002
ST/6
CS 31062−050
M= 1.3 M$_\odot$
[Eu/Fe]^{ini}= 1.5
dil= 0.2 dex
[Fe/H]=−2.41
JOHNSON et al. 2004
ST/2
HD 26
M= 1.5 M$_\odot$
[Eu/Fe]^{ini}= 0.5
dil= 0.8 dex
[Fe/H]=−1.25
VAN ECK et al. 2003
ST/2
HD 187861
M= 1.5 M$_\odot$
[Eu/Fe]^{ini}= 0.5
dil= 0.25 dex
[Fe/H]=−2.3
VAN ECK et al. 2003
ST/24
HD 189711
M= 1.3 M$_\odot$
[Eu/Fe]^{ini}= 0.5
dil= 0.4 dex
[Fe/H]=−1.80
VAN ECK et al. 2003
ST/9
HD 198269
M= 1.2 M$_\odot$
[Eu/Fe]^{ini}= 0.5
dil= 0.4 dex
[Fe/H]=−2.20
VAN ECK et al. 2003
[X^i/Fe]
Atomic number, Z

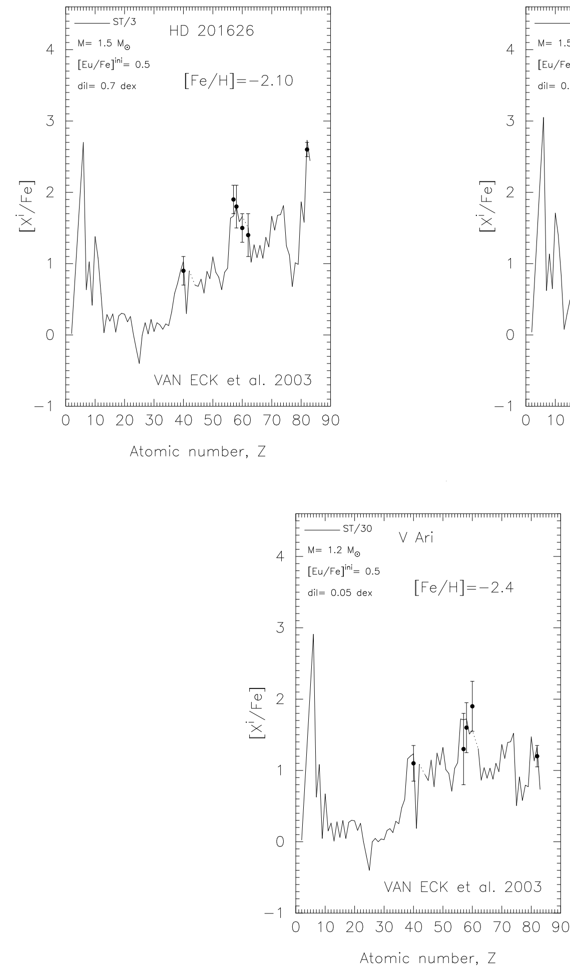


Fig. 4. Fits of a large sample of *s*-rich and lead-rich stars with AGB model predictions.

licities, another intrinsic index is required. In fact at decreasing metallicities [hs/Fe] and [ls/Fe] converge within a small range, while [Pb/Fe] always increases (see the figures in Gallino et al. 2004 - hereafter Paper I). Here, in Figure 1, [hs/ls] is plotted as a function of metallicity for various choices of ^{13}C-pockets. The standard case (ST) is the one that for [Fe/H]=−0.3 best reproduces the main component of the solar system (Gallino et al. 1998). Different ^{13}C-pockets can provide very similar [hs/ls] indices, but still show a large range of [Pb/ls] and [Pb/hs] values. These are plotted respectively in Figure 2 and Figure 3; for instance consider the cases ST*1.3 and ST/3 at [Fe/H]=−2.

3. Comparison of models with observations

Using AGB nucleosynthesis models with different ^{13}C-pockets efficiencies, initial masses and metallicities, we tried to fit the spectroscopic abundances of the *s*-rich and lead-rich stars listed in the Table of Paper I. The fit is made by comparing the element distribution observed in each star with the distribu-

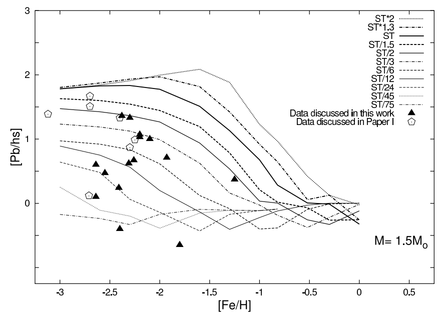


Fig. 3. [Pb/hs] versus [Fe/H] for different ^{13}C-pocket choices. Spectroscopic data of s-rich and lead-rich stars are included for comparison.

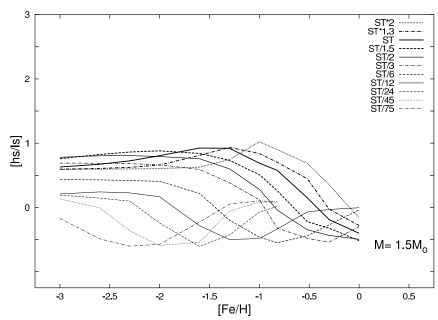


Fig. 1. [hs/ls] versus [Fe/H] for different ^{13}C-pocket choices.

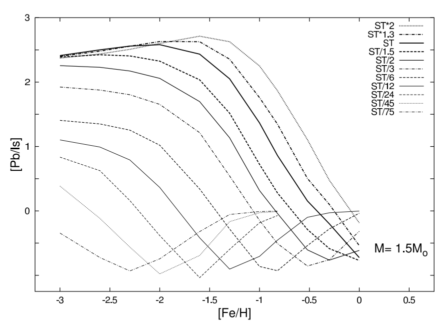


Fig. 2. [Pb/ls] versus [Fe/H] for different ^{13}C-pocket choices.

tion predicted by AGB models with different ^{13}C-pocket efficiencies. Such a large spread is justified by observation of MS, S, C(N), Ba stars in the disk (see Busso et. al 2001; Abia et al. 2002). In Figure 4 we report the fits of lead stars not yet presented in Paper I. To compare our predicted abundances with observations, in many cases we apply a dilution that simulates the effect of mixing of s-rich material in the envelope of extrinsic stars, using the rule: dil=log(M_{env}^{ini}/M_{transf}), where M_{env}^{ini} is the initial envelope mass and M_{transf} is the mass of transfered material. The choice of ^{13}C-pocket efficiency, the initial mass, the initial [Eu/Fe] assumed (see below), the dilution factor and the metallicity are indicated in each plot. In AGB stars of low metallicity, the *s*-process feeds Eu at a consistent level, with a constant ratio $[Ba/Eu]_s \sim 0.7$. For several lead stars the spectroscopic observation indicates a lower [Ba/Eu] ratio than predicted, which may imply a different $[Eu/Fe]^{ini}$ in the parent cloud. Indeed, unevolved halo stars in the same range of metallicity show an average [Eu/Fe] = 0.5, with a large spread Δ[Eu/Fe] = $\pm$ 0.5 dex (see Travaglio et al. 2004). The adopted $[Eu/Fe]^{ini}$ is indicated in each panel of Figure 4. Notice that the rule adopted for $[Eu/Fe]^{ini}$ has been applied also to other elements of major r-process origin, e.g. for all the elements from Eu to Tm. For the star CS 31062-050 (Johnson et al. 2004) lines of Cr and Mn have been detected, and somewhat negative [Cr/Fe] and [Mn/Fe] values have been deduced. The *s*-process in AGB stars produces very little Cr and Mn, however unevolved halo stars in the same range of metallicity show a depletion of both Cr and Mn, with an average [Cr/Fe]= −0.2 and [Mn/Fe]= −0.4 (see e.g., François et al. 2004). As shown in Figure 4 for CS 31062-050, adopting these initial values a satisfatory agreement is reached. For some stars, the observed [Ba/Fe] appears significantly higher than [La/Fe], whereas AGB models predict [Ba/Fe] $\simeq$ [La/Fe]. This may indicate difficulties in the determination of the Ba abundance. In general, lanthanum is a more representative element of the second *s*-peak at neutron magic number, N = 82.

In several cases we need to attain high [hs/ls] values without changing [Pb/hs]; according to our AGB models, those values can be reproduced using lower initial masses with respect to the standard mass of $1.5 M_{\odot}$. Reducing the initial mass corresponds to a decrease in the number of thermal pulses. From the previous discussion it is clear that a general comparison of AGB predictions with all the elements detected provides a better method rather than being restricted to the average ls or hs values. Anyway, in Figure 5 the hs data are compared with AGB predictions in the [Pb/hs] versus [Fe/H], showing that the large spread of spectroscopic data are well fitted within the large spread of ^{13}C-pocket efficiencies adopted.

4. Conclusion

A comparison is made of AGB model predictions of low metallicity with spectroscopic data of a large sample of s-rich and lead-rich stars. Varying the initial mass and adopting a large spread of ^{13}C-pocket efficiencies for a given metallicity a satisfactory reproduction of all data is obtained.

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